EFFECT OF CONSTANT AND VARYING MIXTURE PROPERTIES IN SPARK IGNITION ENGINE COMBUSTION PROCESS USING COMPUTATIONAL FLUID DYNAMICS (CFD)

OMAR BIN ARSHAD

Report submitted in fulfillment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering with Automotive Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

JANUARY 2012

ABSTRACT

This project deals with the numerical setup about the effect of different mixture properties of premixed combustion material using Computational Fluid Dynamic (CFD). Mitsubishi Magma 4G15 is used as the base line engine design for the simulation model. 2000 revolution per minute (rpm) and 1000 iterations are set as the tested speed and the number of iterations per time step respectively. The simulation is started right before the spark ignited and when both valves are closed. The model is simulated at different mixture properties which are constant and varying mixture properties. The constant mixture properties value is taken from previous study. While the varying mixture properties is simulated using kinetic theory where only specific heat, thermal conductivity, and viscosity are varied. Case 1 is set as the constant mixture properties and also as the benchmark case. Case 2 until case 5 is the varying mixture properties with different value of L-J parameters. Case 1 gives only 2.19% of deviation from the experimental result on the peak pressure value and 25% deviation on the peak pressure timing. Meanwhile, for case 2 until case 5, they give as much as 22.34% until 45% deviation on peak pressure value and 100% until 162.5% deviations on the peak pressure timing. The key parameter that caused the results are the L-J parameters, mass fraction burned, and turbulence flame speed. The inaccuracy of the turbulence speed is mostly based on laminar flame speed, thermal conductivity, and specific heat. So, the study of L-J parameter is needed to ensure the perfect result in using kinetic theory approach.

ABSTRAK

Projek ini berkaitan dengan kajian berangka tentang kesan sifat-sifat campuran bahan pembakaran pracampuran yang berlainan menggunakan Perkomputeran Dinamik Bendalir (CFD). Mitsubishi Magma 4G15 digunakan sebagai reka bentuk asas enjin bagi model simulasi. 2000 revulasi per minit (rpm) dan 1000 iterasi ditetapkan sebagai kelajuan enjin dan bilangan iterasi setiap satu langkah. Simulasi bermula sejurus sebelum percikan api dinyalakan dan apabila kedua-dua injap ditutup. Model disimulasikan pada sifat-sifat campuran yang berbeza iaitu malar dan berbeza sifat-sifat campurannya. Nilai untuk sifat-sifat campuran yang malar diambil daripada hasil kajian terdahulu. Manakala sifat-sifat campuran yang berbeza-beza disimulasikan menggunakan teori kinetik di mana hanya haba tentu, kekonduksian terma, dan kelikatan sahaja yang berbeza-beza. Kes 1 ditetapkan sebagai sifat-sifat campuran yang malar dan juga dijadikan sebagai penanda aras. Kes 2 sehingga kes 5 pula adalah sifat-sifat campuran yang berbeza-beza dengan nilai parameter L-J yang berbeza-beza. Kes 1 hanya memberikan sebanyak 2.19% sisihan daripada nilai hasil eksperimen pada tekanan tertinggi dan sisihan sebanyak 25% ke atas masa tekanan tertinggi. Sementara itu, untuk kes 2 sehingga kes 5, mereka memberi sebanyak 22.34% sehingga 45% sisihan pada nilai tekanan tertinggi dan 100% sehingga 162.5% sisihan untuk masa tekanan tertinggi. Parameter utama yang mempengaruhi keputusan adalah parameter L-J, pecahan jisim dibakar, dan kelajuan nyalaan gelora. Ketidaktepatan kelajuan nyalaan gelora disebabkan oleh kelajuan nyalaan lamina, kekonduksian terma, dan haba tentu. Oleh yang demikian, kajian mendalam mengenai parameter L-J diperlukan untuk mendapatkan hasil yang sempurna dengan menggunakan pendekatan teori kinetik.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	Cross sectional area of conducting surface
A_f	Flame area
C_p	Specific Heat
$D_{i,m}$	Diffusion coefficient for species *I* in the mixture
e	Energy
F_i	External body force from interaction with dispersed phase in *i* direction
f_i	Number of modes of energy storage (DOF)
h	Enthalpy
$J_{i,i}$	Diffusion flux of species
k	Thermal conductivity
k_{th}	Laminar thermal conductivity
K_{eff}	Effective conductivity
l_T	Turbulent length scale
m	Mass
$\dot{m}$	Mass rate
m_a	Mass of air
$\dot{m}_a$	Mass flow rate of air
m_f	Mass of fuel
$\dot{m}_f$	Mass flow rate of fuel
M_w	Molecular weight
N	Number of mol
P	Pressure corresponding to burn fraction
P_o	Pressure at start of combustion
P_f	Pressure at end of combustion
Q_{cond}	Constant thickness
R_i	Net of production of species *i* by chemical reaction
S_i	Rate of creation by addition from the dispersed phase
S_L	Laminar flame speed
T	Temperature
ΔT	Temperature difference
u	Displacement in *x* direction

u'	Root mean square (RMS) velocity
u_j	The *jth* Cartesian component of instantaneous velocity
V	Volume
ν	Kinematic viscosity
v_x	Velocity in direction *x*
V_o	Volume at start of combustion
V_f	Volume at end of combustion
Δx	Constant thickness
α_L	Laminar thermal diffusivity
Φ	Equivalence ratio
σ	L-J characteristic length
δ_{ij}	Kronecker delta
τ	Shear stress
τ_T	Turbulent time scale
τ_C	Chemical time scale
ρ	Density
μ	Dynamic viscosity
$\dot{\gamma}$	Strain rate
$\in/k_g$	L-J energy parameter

LIST OF ABBREVIATIONS

AF	Air-Fuel ratio
BDC	Bottom Dead Center
^{o}CA	Crank Angle Degree
CA	Crank Angle
CO_2	Carbon dioxide
CO	Carbon Monoxide
CFD	Computational Fluid Dynamics
DOF	Degree of Freedom
FA	Fuel –Air ratio
H_2O	Water
RMS	Root Mean Square
rpm	Revolution per minute
SI	Spark Ignition
TFSC	Turbulent Flame Speed Closure
3D	Three dimensional

CHAPTER 1

INTRODUCTION

1.1 Project Background

The spark ignition engine is a system that mixed air and fuel together in the intake system prior to entry the engine cylinder. While the both intake and exhaust valve are closed, the piston will move to the top dead center to make a compression. The compression will decreased the volume and in the same time the pressure will increase. Combustion of this mixture inside the engine cylinder is one of the processes that control engine power, efficiency, and emission (Heywood, 1988). Inside the combustion chamber, the oxidation of fuels can releases thermal energy. Then, this energy will be converted into mechanical energy or electrical energy (Razali, 2008). The burned products after combustions are the actual working fluids. The work transfers which provide the desired power output occur directly between these working fluids and the mechanical components of the engine (Heywood, 1988).

From previous experimental method, it is understandable that in-cylinder flow analysis caused high cost and technologies. So that, many engineers invent software to prevent this problem. By doing the simulation of the experiment in the software, the result produced will not affect any cost. Same as Computational Fluid Dynamics (CFD) software, they can represent the model or system in computational model. The software will predict what will happen due to the input parameter. Mixture properties is one of the important parameter that need to be known. By using constant mixture properties, the result is predicted has less than 5% deviation from the experiment. And, by using varying mixture properties, which has different value each crank angle, it is predicted the result is more accurate compared to constant properties. Normally, when each crank angle increase, the temperature will also increase due to the decreasing the volume. Increasing of the temperature will affect the properties value.

1.2 Problem Statement

The study is carried out with purpose to analyze the different of constant and varying mixture properties using CFD method. The stability of the model is difficult to predict. The varying properties approach is rarely done by previous researcher. It is tough to choose the approach to ensure the model has perfect stability. It is expected that more realistic mixture definition will resulted with more accurate results.

1.3 Scope of Study

The analysis of spark ignition engine combustion with constant and variable dependence mixture properties are carried out in the framework of Turbulent Flame Speed Closure (TFSC) model of Zimont. Single operating point at 2000 RPM is simulated to study the feasibility of variable dependence mixture setup. Model is simulated using 1000 number of iteration due to get acceptable result.

1.4 Objectives of the Project

The objective of this research is to study the effect of different mixture properties of premixed combustion material on combustion pressure.

1.5 Flow Chart of the Study

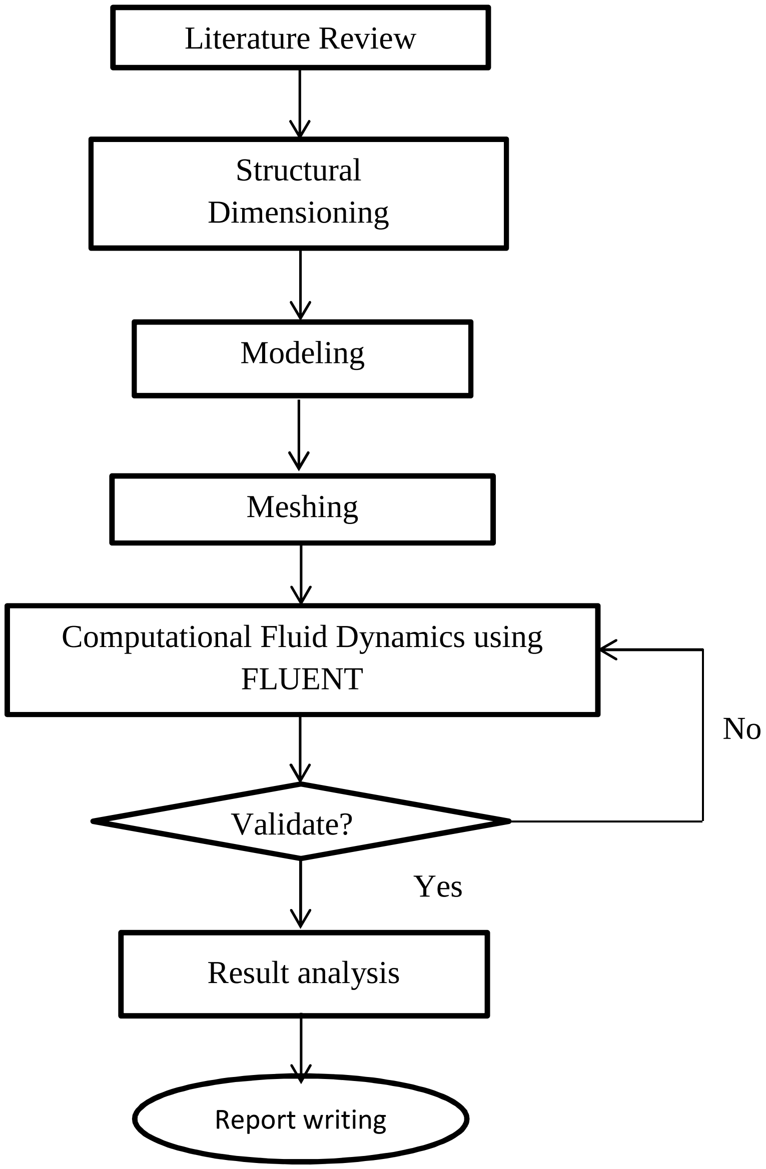

Figure 1.1: Project flow chart

1.6 Organization of Thesis

This thesis consists of five main chapter, introduction, literature review, methodology, result and discussion and the last part is conclusion and recommendation. For Chapter 1 presents some findings that lead to problems statement, objective, scopes and flow chart of work. Chapter 2 is literatures that related to the study and become basic of study framework. Chapter 3 presents the dimensioning work on Mitsubishi Magma 4G15 engine, development of 3D model and generation of computational model. The pre-processing setup is presented in order make the mesh for the model and imported to the solver to analyze. Chapter 4 addresses the validation of the predicted results against experimental results of the cylinder pressure. Chapter 5 presents the important findings of the study and recommendation for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter deals with definition and characteristics of internal combustion engine. Then, the chapter continues with SI engine model which contain (i) intake, (ii) compression, (iii) combustion, (iv) expansion, and (v) exhaust. After that, discussion continues with chemical reaction between isooctane as the fuel and air. Then, discussion continue with fundamental of thermodynamics properties which are (i) density, (ii) specific heat, (iii) thermal conductivity, (iv) viscosity, (v) molecular weight, (vi) laminar flame speed, and (vii) critical rate of strain. Lastly, CFD approach for in-cylinder modelling and effect of constant and variable mixture properties are discussed.

2.2 Internal Combustion Engine

Internal combustion engine is a heat engine that converts chemical energy in fuel into mechanical energy. Chemical energy from fuel will converted into thermal energy from process of combustion or oxidation with air inside the cylinder. This thermal energy will increased the temperature and pressure of gases inside the engine. The high pressure gases will operate the piston downward and moved the mechanical system. The crankshaft will rotate cause of the high pressure of the gas. The crankshaft is connected with the transmission and power train and will transfer the rotating motian into final use (Heywood, 1988).

The internal combustion engine is a system that mixed air and fuel together in the intake system before entering the engine cylinder. After both intake and exhaust valve are closed, the piston will move to top dead center to completing compression. The compression will decreased the volume and in the same time the pressure will increase. Combustion of this mixture inside the engine cylinder is one of the processes that control engine power, efficiency, and emission (Heywood, 1988). Inside the combustion chamber, the oxidation of fuels released thermal energy. Then, this energy is converted into mechanical energy or electrical energy (Razali, 2008). The mechanical energy transfers which provide the desired power output occur directly between these working fluids and the mechanical components of the engine. After the combustion process end, the burned product will be exhausted to the surrounding.

2.3 Principal Operation

The model, which can be programmed in CFD, predicts the cylinder pressure throughout the intake, compression, combustion, expansion and exhaust processes that make up the engine operating cycle. Pressure will be modeled as a function of the crank angle which ran for 720 degrees per cycle or two revolutions because the crank completed two rotations per cycle. The valve and spark timings, engine geometry, engine speed and inlet pressure data will be input into the model (Kuo, 1986).

The individual processes of the engine cycle, intake, compression, combustion, expansion and exhaust, are discussed below in order of occurrence (Kuo, 1986).

2.3.1 Intake

Intake occurs between exhaust valve closing and the start of compression. The intake valve opens before the exhaust valve closes. This period of during both valves are open is called overlapping (Kuo, 1986).

During the overlapping, the model used an s-curve to describe the gradual transition between exhaust pressure and intake or inlet pressure. When the intake valve closes, compression process will occur. The engine speed will determines the time for intake valve closing which fluid will stops flowing into the cylinder (Kuo, 1986).

2.3.2 Compression

During the compression process, both intake and exhaust valves are closed, so that the gases can neither enter nor exit the cylinder. When the piston is moving up-ward and cylinder volume will be decreases. Which will increase the pressure automatically due to the compression of the fluid.

2.3.3 Combustion

There are three major combustion processes of SI engines namely; ignition and flame development, flame propagation, and flame termination as shown in Figure 2.1. Flame development is generally considered the consumption of the first 5% of the air-fuel mixture. During the flame development period, ignition occurs and the combustion process starts, but only a very little pressure rise occurs. Most of the work produced in an engine cycle is the result of the flame propagation period of the combustion process which the period when the bulk of the fuel and air mass is burned. During this period, pressure in the cylinder is greatly increased, providing force to produce work in the expansion stroke (Pulkrabek 1997).

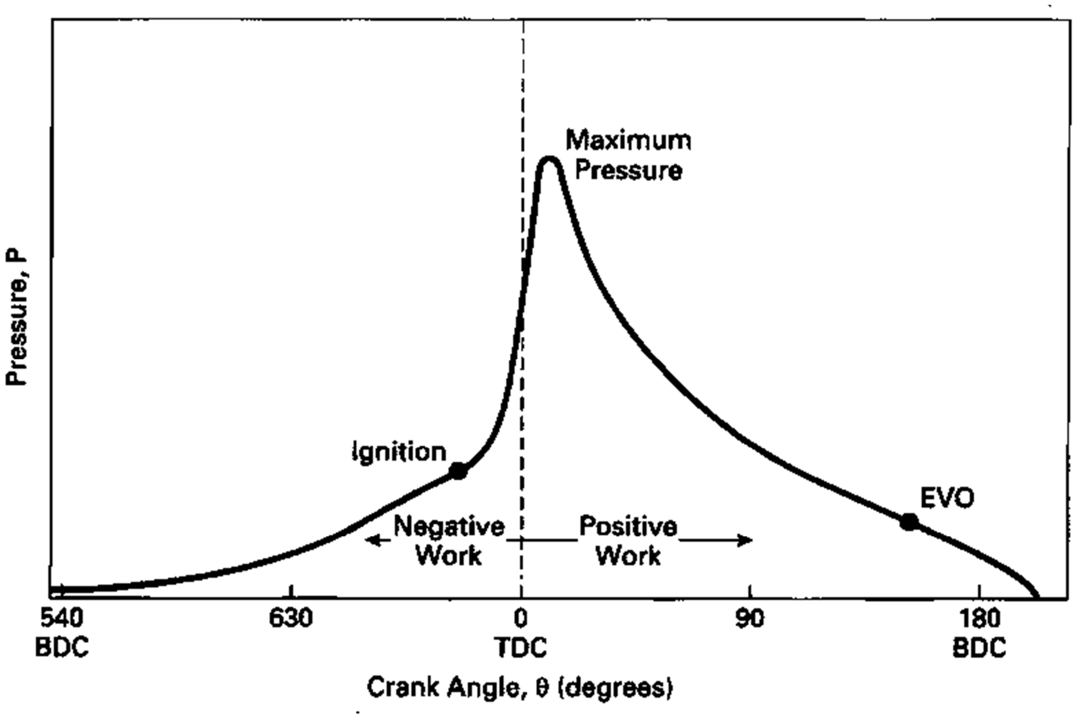

Figure 2.1: In-cylinder pressure profile of SI engine.

Source: Pulkrabek (1997)

2.3.4 Expansion

Expansion process will begin slightly after Top Dead Center (TDC) which is the end of combustion process. The pressure of the burned gases drives the piston down. Work done by turning the crank-shaft will provides power to the car. During expansion, the heat transferred to the cylinder liner is small compared to the work done and the energy lost to internal friction of the gas is also minimum (Kuo, 1986).

2.3.5 Exhaust

Exhaust valve opening occurs before the crank reaches Bottom Dead Center (BDC). At this point, the pressure in the cylinder is much greater than the exhaust system pressure which is around 4-5 atmosphere and the temperature is above 1000 K. The higher pressure in the cylinder will cause a rapid flow of burnt gases going out of the cylinder (Pulkrabek, 1997).

The flow of the gases going out of the cylinder is depends on the area of the opening exhaust valve. The small area of the opening valve will increase the flow. Same goes when the valve is closing. It increases quickly to a maximum, and falls off again as the valve closes. Pressure in the cylinder settles down to the exhaust system pressure as the exhaust valve remains open. The valve closes after TDC, which mean after the overlapping on the next engine cycle (Kuo, 1986).

2.4 Chemical Reaction of Fuel

Most of internal combustion engine gain their energy from combustion of fuel with air. The maximum amount of energy that can be released is when the fuel reacts with a stoichiometric amount of oxygen. Stoichiometric oxygen itself is enough to convert all the carbon in the fuel to CO_2, and all hydrogen to H_2O with no carbon or oxygen left over. The balanced chemical equation of the fuel component, C_8H_{18} burning with stoichiometric oxygen would be (Pulkrabek, 1997):

$$C_8H_{18} + 12.5\ O_2 \rightarrow 8\ CO_2 + 9\ H_2O$$

The component on the left side of the chemical reaction equation is called reactant, while the right side of the equation is called products or exhaust (Pulkrabek, 1997).

A small powerful engine could be built if fuel were burned with pure oxygen. However, the cost that needed to use pure oxygen is very expensive. Usually, air is used as the source of oxygen to react with fuel (Pulkrabek, 1997). Atmospheric air is made up of about 78% of nitrogen, 21% of oxygen, and 1% of argon. Thus, the chemical reaction of fuel and atmospheric air is:

$$C_8H_{18} + 12.5\ O_2 + 12.5(3.76)\ N_2 \rightarrow 3\ CO_2 + 9\ H_2O + 10(3.76)\ N_2 + 5\ CO$$

2.5 Thermodynamics Properties

In thermal design of the internal combustion engines most researchers use air-standard power cycle models to perform their thermodynamic analyses. They used the air-standard to make the comparison reasons in order to show the effect of varying engine parameters, conditions, fluid properties. But, due to the high rise in combustion temperature this assumption becomes less realistic. Although air-standard power cycle analysis gives only approximation to the actual conditions and outputs (Pulkrabek, 1997).

2.5.1 Density

Density is a property that depends on temperature and pressure. The density of most gases is proportional to pressure and inversely proportional to temperature. Density is defined as mass per unit volume (kg/m^3):

$$\rho = \frac{m}{V} \tag{2.1}$$

where

ρ	=	Density
m	=	Mass
V	=	Volume

The density of liquids and solids depends more strongly on temperature than it does on pressure. This is proved when density of water changes from 998 kg/m^3 at 1 atm to 1003 kg/m^3 at 100 atm. The changes are only 0.5%. And the density of water changes from 998 kg/m3 at 20°C to 975 kg/m3 at 75°C. The changes of the density are 2.3% which is greater than changes to pressure (Cengel, 2007).

2.5.2 Specific Heat

The specific heat is known as the energy required to raise the temperature of a unit mass of a substance by one degree. This energy is depends on how the process is finished. There are two kinds of specific heats which are at constant volume and constant pressure (Cengel, 2007). Since there are no constant volumes in the cylinder when the engine is running, specific heat at constant volume is ignored.

By considering a fixed mass in a stationary closed system undergoing a constant-pressure process, conservation of enthalpy principle for this process can be expressed in the differential form (Cengel, 2007).

$$e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}}$$
$$\delta e_{\text{in}} - \delta e_{\text{out}} = dh \qquad (2.2)$$

where

e	=	Energy
h	=	Enthalpy

The left-hand site of the differential equation is the amount of enthalpy that transfers to the system. Thus,

$$Cp = \left(\frac{\delta h}{\delta T}\right)_p \qquad (2.3)$$

where

c_p	=	Specific heat (constant volume)

The values of specific heats are usually used as cold properties. This assumption can be used only for small temperature differences. It will produce greater error in modeling. In order to calculate for the large temperature difference encountered in air-standard power cycles, constant average values of specific heats and specific heat ratios are sometimes used. These average values are evaluated using the extreme temperatures of the cycle, and are believed to yield better results (Abu-Nada, 2006).

For varying mixture properties, kinetic theory is being used to obtain the value of specific heat since in this simulation the density is set as ideal gas (Fluent Inc, 2004) Thus,

$$c_{p,i} = \frac{1}{2}\frac{R}{M_{W,i}}\left(f_i + 2\right) \tag{2.4}$$

where

f_i	=	Number of modes of energy storage (DOF)
R	=	Universal gas constant

2.5.3 Thermal Conductivity

Thermal conductivity is a substance which has an ability to transfer the heat. Usually, a good electric conductor is also a good heat conductor, and therefore they have high value of thermal conductivity, *k*. Material such as rubber and plasticn are not a good conductor. So that, the value of *k* is lower (Cengel, 2007). Based on Fourier's law of conduction.

$$Q_{cond} = kA\frac{\Delta T}{\Delta x}. \tag{2.5}$$

where

Q_{cond}	=	Heat conductor
k	=	Thermal conductivity
A	=	Cross sectional area of conducting surface
ΔT	=	Temperature difference
Δx	=	Constant thickness

Thus,

$$k = \frac{Q_{cond}}{A}\frac{\Delta x}{\Delta T} \qquad (2.6)$$

By using kinetic theory approach, thermal conductivity can be calculated for the varying thermal conductivity in spark ignition engine simulation (Fluent Inc, 2004). Noted that, the density of the model must be set as ideal gas first. The thermal conductivity using kinetic theory is:

$$k = \frac{15}{4}\frac{R}{M_W}\mu\left[\frac{4}{15}\frac{c_p M_W}{R} + \frac{1}{3}\right] \qquad (2.7)$$

where

M_w	=	Molecular weight
μ	=	Computed viscosity
c_p	=	Computed specific heat

2.5.4 Viscosity

Viscosity is a measure of the resistance of a fluid which is being deformed by either shear stress or extensional stress. It is commonly perceived as "thickness", or resistance to flow. Viscosity describes a fluid's internal resistance to flow. Or in other word, viscosity is a measure of fluid friction. Thus, water is "thin", having a lower viscosity, while vegetable oil is "thick" having a higher viscosity. All real fluids (except superfluid) have some resistance to stress, but a fluid which has no resistance to shear stress is known as an ideal fluid or inviscid fluid (Symon 1971). There are two related measure of fluid viscosities namely dynamic viscosity and kinematic viscosity.

(i) Dynamic viscosity which also known as absolute viscosity or the coefficient of absolute viscosity is a measure of the internal resistance. Dynamic viscosity is the tangential force per unit area required to move